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| 13. ABSTRACT (Maximum 200 words)<br><br>Transformation from homogeneous to nonhomogeneous turbulent flows is developed, based on some properties of the Navier-Stokes equations. This transformation is successfully applied to the turbulent wake, produced by a model-scale frigate. Some new schemes for the large-eddy simulations of turbulent flows are developed; tested by direct numerical simulations and compared with experiments. |  |   |  |                            |
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## Final Technical Report

Grant N00014-94-1-0040

"Structure of turbulence and subgrid-scale modeling"

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The project has two major goals, driven by the naval engineering (and many others engineering disciplines) :

1) Reduction of the enormous number of degrees of freedom in turbulent flows to a level that is manageable by computer simulations;

2) Transformations from horizontally homogeneous to nonhomogeneous turbulent flows, produced by ships.

The transformations are necessary because the large-eddy simulations (LES) of free-surface turbulent flows with surface piercing bodies are technically difficult. The following form of transformation was developed, as a starting point :

$$v_i = \frac{\partial b_i}{\partial x_k} w_k - b_k \frac{\partial w_i}{\partial x_k} + (c - \frac{\partial b_k}{\partial x_k}) w_i \quad (1)$$

Here velocity  $w_i$  , produced by LES, is solenoidal ( $\frac{\partial w_k}{\partial x_k} = 0$ ) and statistically homogeneous in horizontal plane (with a nonlinear free-surface approach or a low Frude-number approximation). Constant  $c$  we can put equal to zero for a ship wake,  $b_i$  is a deformation of the flow (see below). From (1) it follows that nonhomogeneous velocity fluctuation  $v_i$  is solenoidal ( $\frac{\partial v_k}{\partial x_k} = 0$ ). The transformation (1) is suggested by the form of the nonlinear terms in the Navier-Stokes equations, written for vorticity. It can be used also for velocity. The Reynolds stress tensor  $\langle v_i v_k \rangle$  is easy to calculate from (1) with a given realization of  $w_i$  and deformation  $b_i$  (symbol  $\langle \rangle$  means statistical or volume averaging). For the deformation in a wake the following formula was used, as a first approximation :

$$b_i = T \langle u_i \rangle, \quad u_i = \langle u_i \rangle + v_i \quad (2)$$

Here  $T$  is a characteristic time,  $\langle u_i \rangle$  is the mean velocity profile in the wake and  $u_i$  is the total velocity field. If we choose  $T$  constant, then deformation (2) is

solenoidal and the last term in (1) is zero (with  $c = 0$ ).

These simple formulas in combination with the Smagorinsky LES (SLES) scheme (for horizontally homogeneous turbulence) were compared with measurements of a model-scale frigate wake. The correlation coefficient, calculated in terms of turbulent energy  $\frac{1}{2} \langle v_k v_k \rangle$ , is surprisingly high ( $\geq 0.80$ ).

In future we plan to test this approach with a more complete data for all components of the Reynolds stress tensor  $\langle v_i v_k \rangle$ . The simple transformation (1)-(2) is designed for a distant part of a wake. In order to come closer to a ship, we may need a more general transformation. For example, we can use double transformation: first from horizontally homogeneous turbulence to a distant wake, then from distant wake to a part of the wake, which is closer to a ship. The second deformation  $b_i^{(2)}$  should reflect near ship hydrodynamics. We can also combine (1) with a wavelet transformation in order to achieve locality in the spectral content. At the same time, we can use (1)-(2) and their generalizations to calculate Reynolds stresses and, thus, to get closed equations for the mean velocity  $\langle u_i \rangle$ .

We made comparison of the SLES scheme with a good experimental data for a high Reynolds number turbulence. SLES reproduces the "-5/3" energy spectrum. However, the third order moment (energy flux), high order moments (intermittency) and probability distribution for the velocity increments, obtained by SLES, deviate significantly from measurements. For future applications, we need a better scheme. We can try some schemes, which we developed in a past (Markov modeling, conditional averaging, incorporation of the intermittency effects in LES, generalization of traditional LES models). But, in order to obtain a reliable scheme systematically, we need a good direct numerical simulations (DNS) data with a substantial inertial range, which means high Reynolds number. To create such DNS data for three-dimensional (3D) turbulence is very difficult. But we can do it for 2D turbulence [calculations on  $(8192)^2$  grid are feasible]. By using local characteristics of 2D turbulence (vorticity gradient) and conditional averaging, we can develop an effective LES scheme, which can be applied to 3D turbulence as well.

In summary, we have two basic issues in the development of this project: 1) LES schemes; 2) transformations from horizontally homogeneous turbulence to nonhomogeneous turbulent flows, produced by ships.

I would like to continue cooperation with experimental laboratory of Mory Gharib at Caltech. In numerical experiments I would like to continue cooperation with Doug Dommermuth at the Science Applications International Corporation.

## TECHNOLOGY TRANSFER

Modeling, large-eddy simulation capability and transformation from homogeneous to nonhomogeneous turbulent flows - cooperation with Dr. D. G. Dommermuth and his group at the Science Applications International Corporation.

## PUBLICATIONS, EMANATING FROM THE PROJECT

1. Novikov, E.A., "Statistical Balance of Vorticity and a New Scale for Vortical Structures in Turbulence," *Phys. Rev. Letters*, **71** (17), 2718-2720, (1993).
2. Kadtke, J.B. and Novikov, E.A., "Chaotic Capture of Vortices by a Moving Body I: The Single Point Vortex Case," *Chaos* **3** (4), 543-553 (1993).
3. Novikov, E.A., "Exact results, obtained by conditional averaging of Navier-Stokes equations," pp.101-106, in "Turbulence in spatially extended systems," (Eds. R. Benzi, C. Basdevant & S. Ciliberto), Nova Science Publishers, 1993.
4. Dommermuth, D.G. and Novikov, E.A., "Direct-numerical and large-eddy simulations of turbulent free-surface flows," Proc. "Sixth International Conference on Numerical Ship Hydrodynamics," Iowa City, 239-270 (1993).
5. Novikov, E.A., "Vortical scales for two- and three-dimensional turbulence," *Physical Review E* **49**(2), Rapid Communications : R975-R977 (1994).
6. Pedrizzetti, G. and Novikov, E.A., "On Markov modeling of turbulence," *Journal of Fluid Mechanics* **280** : 69-93 (1994).
7. Novikov, E.A. and Dommermuth, D.G., "Conditionally-averaged dynamics of turbulence," *Modern Physics Letters B*, **8**(23) : 1395-1401 (1994).
8. Novikov, E.A., "Characteristic scales for a scalar field in turbulent flow," *Journal of Physics A, Math. Gen.*, Letter : L797-L800 (1994).
9. Dommermuth, D.G., Novikov, E.A. and Mui, R.C.Y., "The interaction of surface waves with turbulence," Proc. "ASMA Symposium on free-surface turbulence," Lake Tahoe, 20 pages (1994).
10. Novikov, E.A., "Infinitely divisible distributions in turbulence," *Physical Review E*, **50**(5), Rapid Communications : R3303-R3305 (1994).
11. Novikov, E.A., "Conditionally-averaged dynamics of turbulence, new scaling and stochastic modeling," in Lévy flights and related phenomena in physics (eds. M.F. Shlesinger, G.M. Zaslavsky and U. Frish), p. 37-50, Springer (1995).

12. Novikov, E.A., "Microcirculations in turbulent flows," *Physical Review E*, **52**(3) : 2574-2576 (1995).
13. Novikov, E.A., "Conditional averaging of a turbulent free surface," *Physical Review E*, **52**(5) : 5679-5680 (1995)
14. Pedrizzetti, G., Novikov, E.A. and Praskovsky, A.A., "Self-similarity and probability distributions of turbulent intermittency," *Physical Review E*, **53**(1):475-487(1996).
15. Mui, R.C.Y., Dommermuth, D.G. and Novikov, E.A., "Conditionally averaged vorticity field and turbulence modeling," *Physical Review E*, **53**(3):2255-2259, (1996).
16. Novikov, E.A., "Velocity circulations in free surface flows," *International Journal of Engineering Science*, **34**(3):359-361, (1996).
17. Dommermuth D.G., Gharib M., Huang H.T., Innis G.I., Maheo P., Novikov E.A., Talcott J.C. & Wyatt D.C., "Turbulent Free-Surface Flows: a Comparison between Numerical Simulations and Experimental Measurements", 17 p., Proc. 21 Symp. on Naval Hydrodynamics, Trondheim, Norway, 1996
18. Novikov A. E. and Novikov E. A., "Vortex-sink Dynamics", *Phys. Rev. E*, **54** (4) : 3681-3686 (1996).